STAFF SUMMARY SHEET

	TO	ACTION	SIGNATURE (Surname), GRADE AND DATE		TO	ACTION	SIGNATURE (Surname), GRADE AND DATE
1	DFM	sig	Pettit, Lt Col, 8 Jul 14	6			
2	DFER	approve	Salt?, AD22, 9 July 14	7			
3	DFM	action	(Author /Originator)	8			
4				9			
5				10			

SURNAME OF ACTION OFFICER AND GRADE	SYMBOL	PHONE	TYPIST'S INITIALS	SUSPENSE DATE
Pettit, Lt Col	DFM	333-4189	tjp	

SUBJECT	DATE
Clearance for Material for Public Release USAFA-DF-PA- 378	20140708

SUMMARY

1. PURPOSE. To provide security and policy review on the document at Tab 1 prior to release to the public.

2. BACKGROUND.
Authors: Brian Tobin and Tim Pettit

Title: "Supply Chain Resilience: Assessing Resilience over the Life Cycle of Capital Equipment"

Circle one: Abstract Tech Report X Journal Article Speech Paper Presentation Poster

Thesis/Dissertation Book Other: ________________

Check all that apply (For Communications Purposes):

[] CRADA (Cooperative Research and Development Agreement) exists

[] Photo/ Video Opportunities [] STEM-outreach Related [] New Invention/ Discovery/ Patent

Description: Summary of work completed with AFMC and AFIT.

Release Information: Submission to the International Journal of Logistics - Research and Applications.

Previous Clearance information: (If applicable) Several works while at AFIT (Pettit et al, 2010 and Pettit et al, 2013), Tobin (2010).

Recommended Distribution Statement: Distribution A: Approved for public release, distribution unlimited

3. DISCUSSION. No data on military policy, processes or technologies included -- assessments of weapon systems are sanitized as ex: "Product #10".

4. RECOMMENDATION. Recommend approval for Distribution A.

TIMOTHY J. PETTIT, Lt Col, USAF, PhD
Assistant Professor of Management

International Journal of Logistics: Research and Applications
Vol. XX, No. XX, date, pages

Supply Chain Resilience: Assessing Resilience over the Life Cycle of Capital Equipment

Brian P. Tobin[a] and Timothy J. Pettit[b*]

[a] *Department of Operational Sciences, Air Force Institute of Technology, Dayton, Ohio, USA*

[b] *Department of Management, United States Air Force Academy, Colorado Springs, Colorado, USA*

(Received 16 June 2014; final version received XXXXX)

Abstract

Supply chain resilience is becoming an essential concept for ensuring sustainability of a company. Defined as an enterprise's ability to survive, adapt and grow in the face of turbulent change (Fiksel, 2006), supply chain resilience concepts have great potential for improving supply chain management. To evaluate the various stages of resilience over a product's life cycle, 11 products with long life cycles (e.g. capital equipment) were identified for this study. As exploratory work, each product was segmented into two phases of its life cycle: production and sustainment. This research analyzed data collected on supply chain resilience factors: vulnerabilities and capabilities for each individual product, to determine if differences exist as products progress through the life cycle. The results indicate that the supply chain resilience framework and measurement tool (Pettit, Croxton and Fiksel, 2013) provides managers with beneficial information to assist in the strategic management of their supply chain.

Keywords: resilience, risk management, supply chain management, product life cycle

The views expressed in this article are those of the authors and do not necessarily reflect the official policy or position of the Air Force, the Department of Defense, or the U.S. Government.

1. Introduction

1.1 Background

Beginning in the 1960s the commercial sector was lagging behind the military in the field of logistics. This was evident due to the commercial sector benchmarking concepts and practices that the military had developed for their operations (Russell, 2007). Figure 1 illustrates the United States military's progression from the leader of logistics in the 1950s and 1960s until 2003, where the military is now implementing the commercial sector's best practices by pursuing the concepts, practices, and technologies of supply chain management (Russell, 2007).

The United States Department of Defense (DoD), in 2003, directed the implementation of modern supply chain practices for all DoD components with the release of the DoD Supply Chain Material Management Regulation (DoD 4140.1-R, 2003). This regulation mandates the framework and guiding principles for many aspects of supply chain management and requires all DoD components to measure total supply chain performance (DoDM 4140.1, 2014; Russell, 2007). With subsequent investment in supply chain resilience research beginning in 2005 (Pettit, Fiksel and Croxton, 2010), once again the commercial sector can benefit from the successful experiences of the military supply chain.

* Corresponding author. Email: timothy.pettit@usafa.edu

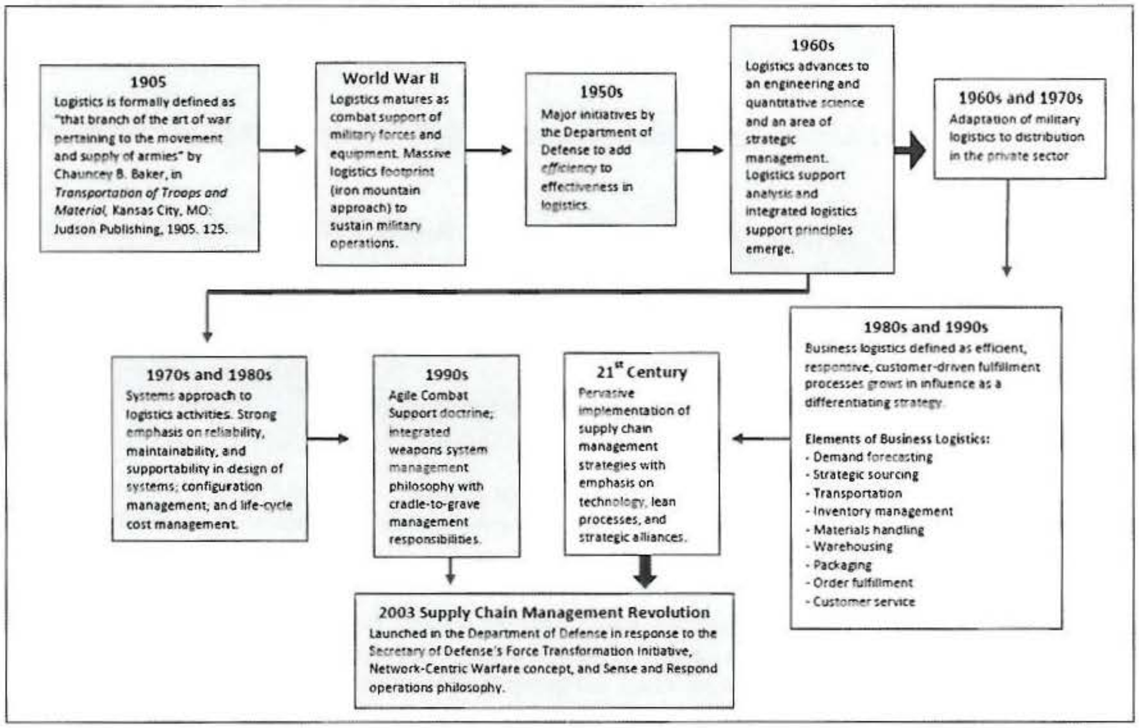

Figure 1: Evolution of Logistics Thought and Practice

(Adapted from Russell, 2007)

1.2 Problem Definition

Supply chain resilience has been identified as a method of enhancing traditional risk management associated with commercial supply chains both in recent literature and research (Christopher and Peck, 2004; Sheffi, 2005; Fiksel, 2006; Manuj and Mentzer, 2008; Ponomarov and Holcomb, 2009; Jüttner and Maklan 2011; Ponis and Koronis, 2012; Pettit, Croxton and Fiksel, 2013). This leads to the problem statement:

Do managerial tools exist to provide a method to enhance current supply chain risk management over a product's life cycle using the new concept supply chain resilience?

This research investigates literature on supply chain resilience to identify proper tools then evaluates the suitability of one such tool. Supply chain resilience has been a topic of research since the globalization of the supply chain and some major unanticipated disruptions, such as the terrorist attacks on the United States on 11 September 2001, Hurricane Katrina from 23 August to 3 September 2005, earthquake and tsunami in Japan on 11 March 2011, and Iceland volcanic eruption of 27 May 2011. This research will focus on the Supply Chain Resilience Assessment and Management (SCRAM) tool (Pettit, Croxton and Fiksel, 2013). The SCRAM tool is used to measure current supply chain vulnerabilities and capabilities, provide recommendations for improvements, and provide information to better prepare supply chain leadership with managing products, processes, and relationships.

1.3 Literature Review

1.3.1 Definition of Supply Chain

There are many different definitions of a supply chain in literature. Stock and Boyer noted 173 individual definitions of supply chain management in journals and books (2009). For the purpose of this research, the supply chain is defined as the network of organizations involved in the upstream and downstream flows of products, services, finances and information from the initial supplier to the ultimate customer (Christopher, 1992; Mentzer et al., 2001; Lambert, Garcia-Dastugue and Croxton, 2005). This definition is important to the research of resilience; it must have a wide view of multi-functions and multi-firms across the supply chain to capture the dynamics of

turbulence and complexity.

1.3.2 Risk Management

Traditional risk management involves risk analysis which includes assessing each risk in terms of its likelihood of occurrence (probability) and the estimated impact (severity) should the risk occur (VanderBok, et. al, 2007). A typical step by step explanation of the risk management process is shown Figure 2, illustrating a continuous circle of risk identifying, assessing, analyzing, controlling, implementing and reviewing (Manuele, 2005). Today's supply chains are much more complex and more susceptible to disruptions due to the globalized supply chains, specialized factories, centralized distribution, increased outsourcing, reduced supplier base, increased volatility of demand, and technological innovations (Cranfield University, 2002). Recent literature identifies the greatest weakness of risk management is its inability to adequately characterize low-probability, high-consequence events (Kunreuther, 2006). Pettit, Croxton and Fiksel noted that "Traditional risk management is a successful tool when potentially disruptive events can be clearly identified" (2013:57).

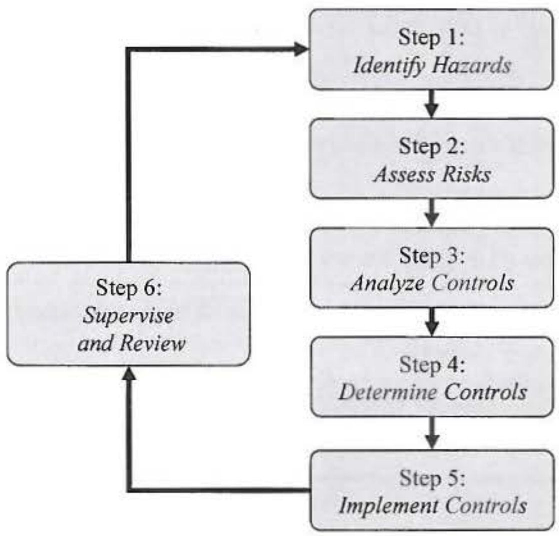

Figure 2: Operational Risk Management Process
(Adapted from: Manuele, 2005)

1.3.3 Resilience

What is resilience? The typical engineering definition of resilience is "the tendency of a material to return to its original shape after the removal of a stress that has produced elastic strain" (Merriam-Webster, 2007:1340). Resilience has been identified as an important concept in other fields of study, such as ecology, psychology, leadership, and the supply chain (Folke et al., 2004; Gorman et al., 2005; Stoltz, 2004; Rice and Caniato, 2003; Sheffi, 2005a; Christopher and Peck, 2004; Fiksel, 2006; and Ponomarov and Holcomb, 2009). Definitions of resilience from the fields of study listed above are summarized in Table 1.

Table 1. Definitions of Resilience

Source	Definition	Field of study
Merriam-Webster (2007)	Capability of a body to ***recover its size and shape*** after deformation	Engineering
Folke et al. (2004)	***Ability to rebound*** from a disturbance while maintaining diversity, integrity and ecological processes	Ecology
Gorman et al. (2005)	***Ability to bounce back*** from adversity	Psychology
Stoltz (2004)	***Ability to bounce back*** from adversity and ***move forward*** stronger than ever	Leadership
Rice and Caniato (2003)	***Ability to react*** to an unexpected disruption and ***restore normal operations***	Supply chain
Sheffi (2005)	***Containment of disruption*** and ***recovery*** from it	Supply chain
Christopher and Peck (2004)	Ability of a system to ***return to its original state*** or ***move to a new, more desirable state*** after being disturbed	Supply chain
Fiksel (2006)	Capacity for complex industrial systems to ***survive, adapt and grow*** in the face of turbulent change	Supply chain
Ponomarov and Holcomb (2009)	Capability to prepare for unexpected events, ***respond*** to disruptions, and ***recover by maintaining continuity of operations*** at the desired level of	Supply chain

1.3.4 Why Resilience?

"Supply chain resilience no longer implies merely the ability to manage risk. It now assumes that the ability to manage risk means being better positioned than competitors to deal with–and even gain advantage from–disruptions" (Sheffi, 2005a:1). Why the interest in supply chain resilience? According to Christopher and Peck, "in an age of lengthening supply chains serving globe-spanning operations, there are frequent reminders that we live in an unpredictable and changing world 2004:1). Fiksel added, "the old methods of risk management are no longer effective in a global economy that is tightly connected and unpredictable" (The Ohio State University, 2008:1). Fiksel also stated "companies must cope with a continuous stream of surprises, ranging from industrial accidents to economic shocks to natural catastrophes" and "resilience is about configuring company assets, including both human and economic capital, in a way that maximizes the capacity of the enterprise to survive, adapt and grow in the face of turbulent change" (The Ohio State University, 2008:1).

The study of supply chain resilience was spurred by the disruptions in the United Kingdom's (UK) transportation network due to fuel protests in 2000 and by the UK's beef market facing an outbreak of Foot and Mouth Disease in 2001 (Peck, 2005). Additionally, there are many examples of disruptions that demonstrate the importance of resilience. For example, a lightning bolt that, in March 2000, struck a Philips semiconductor plant in Albuquerque, New Mexico, created a 10-minute blaze that contaminated millions of chips and subsequently delayed deliveries to its two largest customers: Finland's Nokia and Sweden's Ericsson. The resulting supply chain disruption contributed to Ericsson to leaving the mobile phone business due to the losses it sustained, but Nokia prevailed because the company recognized the magnitude of the disruption early on and took immediate action because it was resilient (Sheffi, 2005b). Also, the 2002 longshoreman union lockout at the Los Angeles/Long Beach ports interrupted transshipments and deliveries to many US-based firms. Port operations and schedules did not return to

normal until six months after the strike ended. This 10-day strike did not interrupt Dell Computer's operations like it did for many of the other country's retailers and manufacturers. Dell was aware that its lean, high-speed business model left it vulnerable. Dick Hunter, in charge of Dell's United States supply chain, stated "when a labor problem or an earthquake or a SARS epidemic breaks out, we've got to react quicker than anyone else" (Breen, 2004:86). Dell recognized its vulnerabilities and took steps to make sure they, as a firm, are resilient. In a world of turbulent change, resilience is a key competency, since even the most carefully designed supply chain is susceptible to unforeseen factors. Businesses must be prepared to cope with a continuous stream of challenges, ranging from human errors to technological failures to natural disasters. The ability to manage the risk of uncertainty is a challenge and that businesses are always changing and change introduces risk, and this requires resilience. Sheffi stated, "Some organizations cope far better than others with both the prospect and the manifestation of unquantifiable risk. They don't have in common a secret formula or even many of the same processes for dealing with risk, but they share a critical trait: resilience" (2005a:1).

1.3.5 Resilience Framework

Since the UK's fuel protests in 2000 and the many other major disruptions around the globe, there have been many who have investigated supply chain resilience to define its characteristics and impacts. A review of extant literature identified vulnerabilities as one of the characteristics of supply chain resilience (Peck, 2005; Sheffi, 2005b; Ponomarov and Holcomb, 2009). Pettit, Fiksel and Croxton defined supply chain vulnerabilities as "fundamental factors that make an enterprise susceptible to disruptions" (2010:6). They are categorized as Turbulence, Deliberate threats, External pressures, Resource limits, Sensitivity, Connectivity and Supplier/Customer disruptions.

The other characteristic that literature identified in supply chain resilience is capabilities (Cranfield, 2003; Fiksel, 2006, Peck, 2005; Sheffi, 2005; Ponomarov and Holcomb, 2009). Pettit, Fiksel and Croxton defined supply chain capabilities as the "attributes that enable an enterprise to anticipate and overcome disruptions" (2010:6). Capabilities are categorized as Flexibility in sourcing, Flexibility in order fulfillment, Capacity, Efficiency, Visibility, Adaptability, Recovery, Dispersion, Collaboration, Organization, Market position, Security and Financial strength.

1.3.6 How to Measure Resilience

Many scholars agree that supply chain resilience is essential in today's global environment (Christopher and Peck, 2004; Sheffi, 2005b; Ponomarov and Holcomb, 2009; Pettit, Fiksel, and Croxton 2010). However, the ability to measure supply chain resilience without using traditional risk management techniques had been lacking in literature. Based on the framework of Pettit, Fiksel and Croxton (2010), the Supply Chain Resilience Assessment and Management (SCRAM) tool was created (Pettit, Croxton and Fiksel, 2013).

These authors stated that through the measurement of vulnerabilities and capabilities they could provide an evaluation of a supply chain's current level of resilience, and from this developed the supply chain resilience assessment and management tool to direct supply chain improvements. The tool is designed to subjectively measure the vulnerability and capability factors and their respective sub-factors. The target population for SCRAM included all business organizations, both for-profit and not-for-profit, global companies and privately owned small businesses, as well as corporations and governmental agencies (Pettit, Croxton and Fiksel, 2013). It is a web-based survey instrument that measures responses in ordinal form using a Likert Scale "Disagree/Agree," ranging from 1 to 5. Due to the large number of factors and sub-factors (21 and 111, respectively), the study controlled the number of questions in order to maintain a reasonable survey length (Dillman, 2000). The authors proposed that the assessment of the resilience factors can be used to evaluate an organization's current state of resilience within its supply chain, and therefore, through a strategic review of the organization's resilience, suggest recommendations for improvements that can be prioritized to meet strategic goals and financial limitations. The recommendations are designed to lead an organization to a state of "balanced resilience" (see Figure 3). Definitions of each factor and lists of sub-factors are shown in Tables 2 and 3.

Research indicated that the SCRAM tool is a viable method of evaluating the levels of vulnerabilities and capabilities of a firm's supply chain. Presentation of results to corporate sponsors provided excellent feedback as to the breadth of the supply chain resilience framework and the ability of the SCRAM tool to accurately measure the sources of change facing the firm as well as the firm's strengths and weaknesses (Pettit, Croxton and Fiksel, 2013).

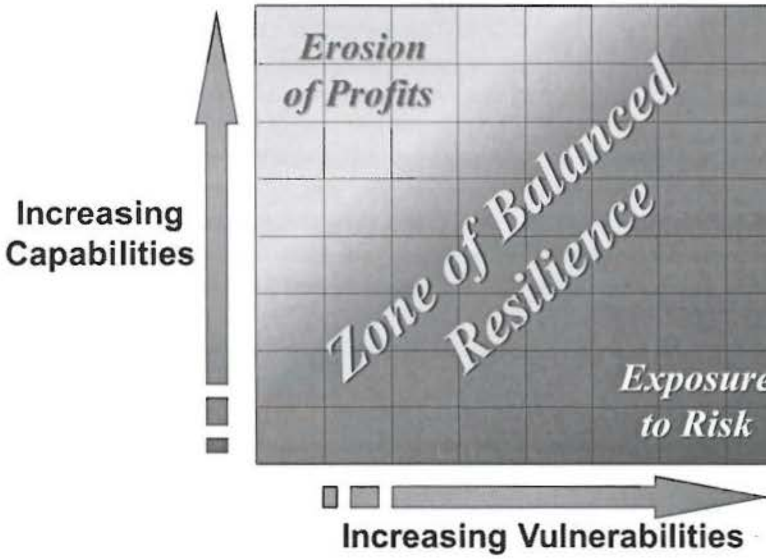

Figure 3. Zone of Balanced Resilience (Pettit, Fiksel and Croxton, 2010)

Table 2. Vulnerability Factors

Vulnerability Factor	Definition	Sub-Factors
Turbulence	Environment characterized by frequent changes in external factors beyond your control	Natural disasters, Geopolitical disruptions, Unpredictability of demand, Fluctuations in currencies and prices, Technology failures, Pandemic
Deliberate threats	Intentional attacks aimed at disrupting operations or causing human or financial harm	Theft, Terrorism/sabotage, Labor disputes, Espionage, Special interest groups
External pressures	Influences, not specifically targeting the firm, that create business constraints or barriers	Competitive innovation, Social/Cultural change, Political/Regulatory change, Budget constraints, Corporate responsibility, Environmental, Health and Safety Concern
Resource limits	Constraints on output based on availability of the factors of production	Supplier, Production and Distribution capacity, Raw material and Utilities availability, Human resources
Sensitivity	Importance of carefully controlled conditions for product and process integrity	Complexity, Product purity, Restricted materials, Fragility, Reliability of equipment, Safety hazards, Visibility to stakeholders, Symbolic profile of brand, Concentration of capacity
Connectivity	Degree of interdependence and reliance on outside entities	Scale of network, Reliance upon information, Degree of outsourcing, Import and Export channels,

Note: As modified by Pettit, Fiksel, and Croxton (2010)

Table 3. Capability Factors

Capability Factor	Definition	Sub-factors
Flexibility in Sourcing	Ability to quickly change inputs or the mode of receiving inputs	Part commonality, Multiple uses, Supplier contract flexibility, Multiple sources
Flexibility in Manufacturing	Ability to quickly and efficiently change the quantity and type of outputs	Modular product design, Delayed commitment/ Production postponement, Small batch sizes, Equipment change over
Flexibility in Order Fulfillment	Ability to quickly change outputs or the mode of delivering outputs	Alternate distribution channels, Risk pooling/sharing, Multi-sourcing, Inventory management, Re-routing
Capacity	Availability of assets to enable sustained production levels	Reserve capacity, Redundancy, Backup energy and comm
Efficiency	Capability to produce outputs with minimum resource requirements	Waste elimination, Labor productivity, Asset utilization, Product variability reduction, Failure prevention
Visibility	Knowledge of the status of operating assets and the environment	Business intelligence, Information technology, Product, equipment and people visibility, Information exchange
Adaptability	Ability to modify operations in response to challenges or opportunities	Fast re-routing of requirements, Lead time reduction, Strategic gaming and simulation, Seizing advantage from disruptions, Alternative technology, Learning
Anticipation	Ability to discern potential future events or situations	Early warning signals, Forecasting, Deviation/near-miss analysis, Risk management, Business continuity planning, Recognition of opportunities
Recovery	Ability to return to normal operational state rapidly	Crisis management, Resource mobilization, Communications strategy, Consequence mitigation
Dispersion	Broad distribution or decentralization of assets	Distributed decision-making and Assets, Decentralization of key resources, Empowerment, Dispersion of markets
Collaboration	Ability to work effectively with other entities for mutual benefit	Collaborative forecasting, Customer management, Communications, Postponement, Life cycle management, Risk sharing
Organization	Human resource structures, policies, skills and culture	Accountability, Creative problem solving, Cross-training, Substitute leadership, Learning/benchmarking, Culture
Security	Defense against deliberate intrusion or attack	Layered defenses, Access restrictions, Employee involvement, Collaboration with governments, Cyber-security, Personnel security
Financial Strength	Capacity to absorb fluctuations in cash flow	Insurance, Portfolio diversification, Financial reserves and liquidity, Price margin
Product Stewardship	Assurance of sustainable business practices throughout product life cycle	Monitor environmental, health and safety, Communicate sustainability with Suppliers, Communicate disposal requirements with Customers

Note: As modified by Pettit, Fiksel, and Croxton (2010)

1.4 Research Questions

To date, research conducted utilizing resilience assessment tools to measure vulnerabilities and capabilities of a supply chain have not been applied across various stage of the product life cycle. This indicates the opportunity for the following research question to be investigated:

Research Question: Is the SCRAM tool able to measure supply chain vulnerabilities and capabilities within the product life cycle framework and provide useful feedback?

To answer the research question, the following investigative questions will be addressed:

Question 1: Will the SCRAM tool identify an overage of capabilities compared to vulnerabilities in selected products at a current point in time in the weapon system life cycle?

Question 2: Will the SCRAM tool identify an underage of capabilities compared to vulnerabilities in selected weapon system at a current point in time in the weapon system life cycle?

Question 3: Do supply chain vulnerabilities and capabilities vary across different phases of the product life cycle?

2. Method

This research will use a qualitative assessment methodology to address the research and investigative questions. Data sample will come from U.S. Air Force weapon systems (e.g. aircraft) that represent a sub-sample of high-value, long life-cycle assets, referred to as capital equipment. The SCRAM tool will be used to identify vulnerabilities and capabilities within each supply chain. The products will be organized into two groups based on their current position within the life cycle. Phase I is identified as including products from conception through production, and Phase II is identified as products from post production through disposal (see Figure 4). To answer the investigative questions, the individual product assessments will be analyzed by statistical methods to identify if the SCRAM tool will measure overages and underages of capabilities verses current vulnerabilities; therefore, directly addressing the measurement of balanced resilience within the current supply chain. Additionally, the complete set of product assessments will be statistically compared to analyze if differences between life cycle phases can be identified.

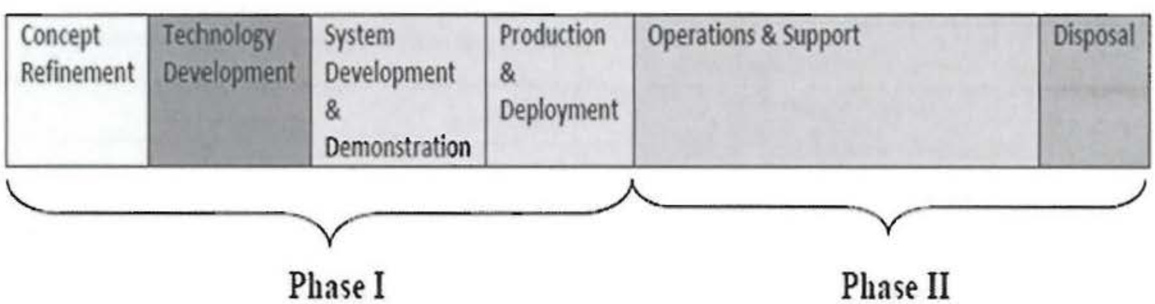

Figure 4. The Product Life Cycle with Phases as Defined in this Study
(Adapted from Defense Acquisition University, 2009)

Subjects are mid-level managers directly responsible for overseeing supply chain operations. Managers were selected by the sponsoring agency for their expertise in the wide variety of functional areas that create supply chain management. These cross-functional teams included managers from, but not limited to, functional roles such as engineering, procurement, program management, research and development, logistics, and financial management. Each team was to include a minimum of five members to reduce individual bias. The SCRAM tool includes a total of 152 questions. SCRAM is a web-based instrument that firms administer to self-assess their current state of supply chain resilience.

3. Results

3.1 Participant Flow

The population for this study includes supply chain managers of capital equipment, defined as high-value, long-life equipment assets. The sample for this study comes from managers of manned and unmanned military aircraft including attack, bomber, cargo, fighter, intelligence-gathering and tanker aircraft. Within the total of 450 investment programs (AFLCMC, 2013), there were 21 capital equipment supply chains identified as sample "products" by the sponsoring organization. A request letter was distributed to the leadership of these organizations, and 11 agreed to participate in the project, representing a 52% response rate.

Each organization's leadership was asked to identify a cross-functional team of top-level supply chain managers for this study. A supply chain cross-functional team should include, but not limited to, such functional roles as acquisition, engineering, budgeting/finance, logistics, manufacturing, procurement, sustainment and program management. Each team was to include a minimum of five members, with no maximum stated. The minimum number of five participants was chosen to get a varied sample of top-level, cross-functional participants and to limit individual bias. Table 4, displays the number within each functional role represented per product and the 54 total participants from the 11 product-lines.

Table 4. Functional Roles by Product

Product #	Acquisitions	Engineering	Finance	Logistics	Manufacturing	Procurement	Sustainment	Program Manager	Total Number of participants
1	1	1	1				1	1	5
2		1		1		1		2	5
3							5		5
4		1		1		1		2	5
5	2	1		1				2	6
6				3					3
7		1		1		1	1	1	5
8	1				1		1	2	5
9	1	2				1		1	5
10	1	1	1	1		1			5
11	1	1	1	1		1			5
Total	7	9	3	9	1	6	8	11	54

3.2 Administration of the Instrument

SCRAM is a web-based instrument to self-assess supply chain resilience. Web-based or internet surveys are a low cost method compared to traditional research methods, such as telephone, mail, and fax surveys (Griffis, Goldsby and Cooper, 2003; Maronick, 2009). The survey instrument was reviewed and approved by the Institutional Review Board. Identified subjects were sent a survey link via business email, with a follow-up two weeks later, with maximum of 2 reminders. The assessment took an average of 27 minutes per person to complete. Responses were voluntary and anonymous, thus allowing a guarantee of no adverse effects for non-participation.

3.3 Baseline Data

The SCRAM tool includes a total of 152 questions. Table 5 includes counts of the experience levels of the respondents in both their current function and within their current organization. With 29 of the 54 respondents (53%) having more than 10 years of experience in their functional role, this lends credit to the assumption that the respondents are subject matter experts. A note of interest is the number of respondents that have less than five years in their current organization; however, this is typical of the sample population due to the transition of employees from turn-over and career advancement.

Table 5. Completion Times with Knowledge Levels

	Average Time to complete	**Time in current Functional Role** *(number of respondents)*				**Time in current Organization** *(number of respondents)*			
Product #	*(mm:ss)*	<1 year	1- <5 years	5 - <10 years	More than 10 years	<1 year	1- <5 years	5 - <10 years	More than 10 years
1	16:00	1	1	1	2	1	3	1	
2	36:47		3		2	1	4		
3	17:30	1	2		2	1	2		2
4	24:33		1	1	3	3	2		
5	46:30	1			5	1	4		1
6	39:10		1	1	1	2	1		
7	18:50		1	2	2		3	1	1
8	38:03	1			2	3		2	
9	18:38	1	2		2	5			
10	27:12				5	3	2		
11	17:33		2		3	2	3		
Average	27:21								
Total # of respondents		5	13	7	29	19	25	6	4
% of respondents		9%	24%	13%	54%	35%	46%	11%	7%

3.4 Statistics and Data Analysis

3.4.1 Analysis of Questions 1 and 2: Identification of Overage/Underage of Capabilities

The data collected from each product's resilience self-assessment is used for the analysis of this research. Two separate methods were used to answer each research question. To answer Research Questions 1 and 2, the data collected from each product's SCRAM was used to calculate a small-sample confidence interval for the sample population mean (McClave, Benson and Sincich, 2008). Due to the small sample size, three to six respondents, both parametric and nonparametric methods were explored. For this set of research questions, parametric methods were used since 94% of all samples were calculated to come from a normal distribution at the 95% confidence level and "the t-test provides Type I error rates close to the 5% nominal value in most of the cases...[with] acceptable power (i.e., 80%)" (de Winter, 2013). Each resilience gap is computed, based on the SCRAM responses using a standard

Likert scale of 1 to 5, by the equation $R_{i,j} = \frac{4-Vi+Cj}{8} - 0.5$, positive values indicating an overage of capabilities as compared to balanced resilience and negative values indicating an underage. This resilience score (R) is calculated from each product's individual assessment answers. The resilience scores for all respondents were then averaged to get the mean R score and standard deviation. The critical t-statistic values were obtained (McClave, Benson and Sincich, 2008). Confidence intervals were calculated using $\bar{x} \pm t_{\frac{\alpha}{2}} \frac{s}{\sqrt{n}}$, where $\bar{x}$ is the mean, **t** is the test statistic, s is the sample standard deviation, and n is the sample size. Therefore, each resilience gap can be assessed for positive (Erosion of resources) or negative (Exposure to risk) or balance (Balanced resilience) with statistical significance. An example result is shown in Table 6 of significant resilience gaps, using Product #10's SCRAM results. Increased sample size is recommended during implementation (N=20+, Pettit, Croxton and Fiksel, 2013). This procedure demonstrates the ability to statistically assess resilience gaps based on qualitative assessment of capabilities and vulnerabilities, thus answering Research Question 1 and 2.

Table 6. Example Results of Resilience Gap Computations

Product #10		Turbulence	Deliberate Threats	External Pressures	Resource Limits	Sensitivity	Connectivity
		V1	V2	V3	V4	V5	V6
Flexibility in Sourcing	C1	9.6% **	8.7%		7.3%	1.8%	0.8%
Flexibility in Manufacturing	C2	2.2%		-4.7%	-0.1%	-5.7%	
Flexibility in Order Fulfillment	C3	7.9%			5.6%	0.1%	
Capacity	C4	-1.0%	-5.3%	-9.5%	-4.3%	-13.4%	-8.5%
Efficiency	C5	6.9%		0.0%	4.6%	-1.0%	0.5%
Visibility	C6	-0.8%	3.8%		3.6%	-4.2%	-8.8% ***
Adaptability	C7	6.1%	5.3%	-0.7%	3.9%	-1.7%	-1.1%
Anticipation	C8	6.5%	5.7%	-0.3%	4.3%	-1.3%	-0.8%
Recovery	C9	6.1%	5.3%	-0.8%	3.8%	-1.7%	3.3%
Dispersion	C10	-0.4%	-1.3%			-8.2%	-8.5% *
Collaboration	C11	5.0%	4.1%			-2.9%	-1.8%
Organization	C12	4.3%			2.0%	-3.5%	
Security	C13		9.5%				4.2%
Financial Strength	C14	3.1%	2.2%			-4.7%	
Product Stewardship	C15		6.7%	0.7%	5.3%	-0.3%	1.4%

Note: * P = 0.10, ** P = 0.05, *** P = 0.01, N = 3 to 6

3.4.2 Analysis of Research Question 3: Does Resilience vary over the Product Life Cycle?

To answer Research Question 3, the products' SCRAM results were grouped into the two phases, Phase I and Phase II. Again, due to the small sample size, Phase I with a sample size of N=5 and Phase II with a sample size of N=6, both parametric and nonparametric statistical methods were explored. Investigation recommended the nonparametric method, Wilcoxon rank sum test, due to the results being more conservative than the parametric

method. Group averages are presented below in Figure 5. However, it is clear from a managerial perspective that combining factors to an overall resilience score does not allow for changes in control mechanisms (capabilities) or supply chain structure (vulnerabilities). Hence Table 7 drills-down to resilience gaps at the factor level (sub-factor resilience gaps were evaluated but are not shown here).

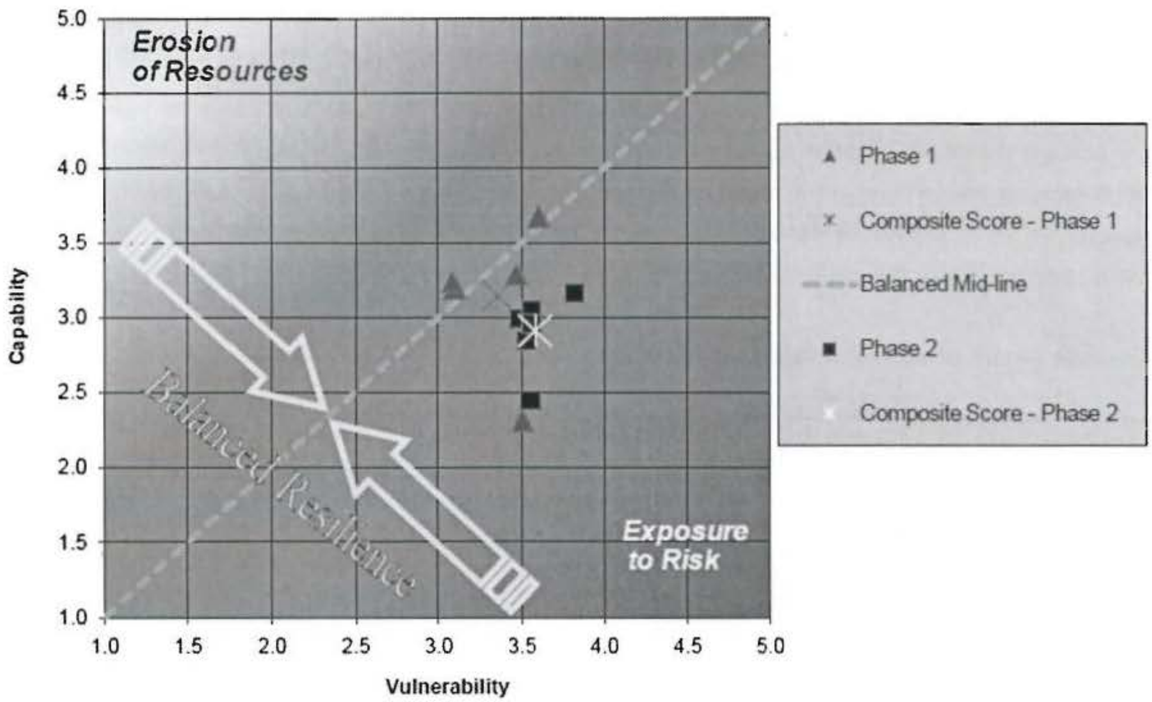

Figure 5. Phase Comparison of Resilience Assessments

Table 7. Comparison of Resilience Gaps by Phase

Resilience Gap, % (Phase I / Phase II)		Turbulence	Deliberate Threats	External Pressures	Resource Limits	Sensitivity	Connectivity
		V1	V2	V3	V4	V5	V6
Flexibility in Sourcing	C1	-18.5 / -25.8	0.7 / -3.5		-6.4 / -20.2	12.4 / 6.0	8.4 / 2.4
Flexibility in Manufacturing	C2	-11.6 / -15.5		-16.0 / -17.9		-0.9 / -2.0	
Flexibility in Order Fulfillment	C3	5.6 / 1.0				4.5 / -3.3	
Capacity	C4	-10.0 / -12.8	-24.2 / -26.7	-0.2 / -4.8	2.6 / -6.2	3.5 / -0.5	-23.2 / -27.8
Efficiency	C5	-3.3 / -14.5		-8.6 / -20.0	4.8 / -11.0	12.5 / 0.7	-14.6 / -26.8
Visibility	C6	-4.9 / -7.1	3.0 / 7.3			21.8 / 16.3	-16.1 / -22.3
Adaptability	C7	1.7 / -8.3	9.1 / 3.3	2.8 / 2.0		10.8 / 1.0	2.4 / -3.6
Anticipation	C8	1.5 / -10.6	4.0 / -8.9	0.0 / -19.5	6.9 / -8.3	20.7 / 8.8	-2.9 / -16.9
Recovery	C9	10.6 / 0.7	9.8 / -1.1		1.2 / -12.9	5.2 / -5.7	-0.3 / -11.0
Dispersion	C10	8.4 / 3.4	15.3 / 11.0			46.2 / 32.1	1.4 / -3.3
Collaboration	C11	-0.1 / -10.5	3.6 / -9.0			19.5 / 10.0	-6.9 / -16.2
Organization	C12	6.3 / -3.2			0.0 / -12.0	27.8 / 17.2	
Security	C13		-21.6 / -21.9				-30.0 / -27.3
Financial Strength	C14	9.6 / 3.2	-6.6 / 0.6			-4.7 / -12.4	
Product Stewardship	C15		5.3 / -0.8	4.4 / -4.9	10.6 / 1.7	12.0 / 3.2	1.5 / -7.1

Notes: Yellow indicates average gap decreased from Phase I to Phase II
Green indicates average gap increased from Phase I to Phase II
No highlight indicates the average gap remained within a 5% point tolerance

As stated, a nonparametric method is used to compare the distributions of Phase I against Phase II in order to indicate differences in the phases as product mature in their life cycle. The appropriate nonparametric method determined is the Wilcoxon rank sum test. This method does not specify the shape or type of probability distribution, but does require two conditions for a valid test (McClave, Benson and Sincich, 2008):

A. The two samples are random and independent
B. The two probability distributions from which the samples are drawn are continuous

The Wilcoxon rank sum test also has the added effect of "moderating the influence of outliers" (Rice, 1995:403), and in applying each sample's average resilience gap (R) rather than an individual subject's capability or vulnerability rating, the variable is now continuous. The results are presented in Table 8, with both the 2-sample test with normal approximation and the 1-way Chi-squared test in agreement for all cases. These tests identified two of the six vulnerability factors varied between Phase I and Phase II at a confidence level of 90%, and six of the 15 capability factors varied between phases. Larger scale implementation is expected to increase the significance. Table 9 summarizes the factors and the direction of the change.

Table 8. Test for Differences between Phases

	V1	V2	V3	V4	V5	V6
2-Sample Test, normal approx.	0.0828	1.0000	0.0277	0.1207	0.2353	0.4642
1-way Test, Chi-squared	0.0679	1.0000	0.0219	0.1003	0.2012	0.4102
Reject?	***Reject***		***Reject***			

	C1	C2	C3	C4	C5	C6	C7
2-Sample Test, normal approx.	0.2353	0.0552	0.2353	0.4632	0.0225	0.2002	0.0225
1-way Test, Chi-squared	0.2012	0.0446	0.2012	0.4092	0.0176	0.1699	0.0176
Reject?		***Reject***			***Reject***		***Reject***

	C8	C9	C10	C11	C12	C13	C14	C15
2-Sample Test, normal approx.	0.0222	0.0358	0.4113	0.0358	0.4113	0.7837	0.1207	0.1709
1-way Test, Chi-squared	0.0174	0.0285	0.3613	0.0285	0.3613	0.7144	0.1003	0.1441
Reject?	***Reject***	***Reject***		***Reject***				

Notes: Null Hyp: Phase I = Phase II

Alt Hyp: Phase I ≠ Phase II

Table 9. Summary of Significant Changes between Phases

	V1	V2	V3	V4	V5	V6
Phase I to Phase II			Increased			

	C1	C2	C3	C4	C5	C6	C7
Phase I to Phase II					Decreased		Decreased

	C8	C9	C10	C11	C12	C13	C14	C15
Phase I to Phase II	Decreased	Decreased		Decreased				

From the data collected from the SCRAM 2.0 assessment of 11 capital equipment supply chains and the presented analysis, it is thus able to positively answer Research Question 3 as a suitable process for assessing differences between life cycle phases.

4. Discussion

Previous research presented opportunities for improvement with the supply chain risk management process for long-life, high-value assets. For these capital equipment supply chains, this research investigated literature in the field of supply chain resilience and identified the Supply Chain Resilience Assessment and Management (SCRAM) tool as an avenue for potential improvement in risk management efforts.

4.1 Research Questions

Based on the results of this study using SCRAM assessments within two well-defined phases of the product life cycle, the results support a positive answer to the overall research question: Is the SCRAM tool able to measure supply chain vulnerabilities and capabilities within the product's life cycle and provide useful feedback? Significant statistical differences were found, thus recommending this analysis process for implementation of the SCRAM tool. Though these results are not without limitations, the results show promise for the utility of supply chain resilience to enhance current supply chain risk management processes.

4.2 Managerial Implications

The SCRAM tool assessment results have shown in previous research that the assessment tool can identify an organization's current level of resilience by measuring the organization's supply chain vulnerabilities and capabilities (Pettit, Croxton and Fiksel, 2013). This research confirmed the ability to measure vulnerabilities and capabilities, and through statistical analysis, to identify an imbalance of specific vulnerabilities and capabilities indicating resilience concerns toward either eroding profitability or operating in excessive risks. The results also extend previous research into the statistical comparison between life cycle phases of these capital equipment supply chains, which indicates that the tool can also be used to strategically plan for resilience changes as products mature. This information can provide supply chain leaders the ability to apply corrective measures based on resilience constructs.

4.3 Future Research

There are many opportunities for improvement and future research in the field of supply chain resilience. A more targeted study of a capital equipment supply chain with a larger sample size would be beneficial. Additionally, the research could be expanded by dividing the product life cycles into more distinct phases to identify more differences as systems mature. Future research could explore the supply chain from not only the focal company's perspective, but also the suppliers and customers up and down the supply chain. Furthermore, a longitudinal study to follow multiple products as they mature will validate both the changes in resilience but also identify target portfolios of capability within specific life cycle phases. And finally, the opportunity to conduct cost analyses of supply chain resilience enhancements and their benefits would assist in future estimations of the return-on-investment for strategically managing supply chain resilience.

References

Air Force Life Cycle Management Center. (2013). A revolution in acquisition and product support. Retrieved from www.wpafb.af.mil/shared/media/document/AFD-130523-047.pdf.

Breen, B. & Aneiro, M. (2004). Living in Dell time. *Fast Company,* (88), 86-96.

Christopher, M. (1992). Logistics and supply chain management, London: Pitman Publishing.

Christopher, M. & Peck, H. (2004). Building the resilient supply chain. *International Journal of Logistics Management*, *15*(2), 1-13.

Cranfield University. (2002). Supply chain vulnerability: executive report, Bedford, UK: School of Business, Cranfield University.

Cranfield University. (2003). Creating resilient supply chain: a practical guide. Bedford, UK: Centre for Logistics and Supply Chain Management, Cranfield University.

Defense Acquisition University. (2009). Defense acquisition guidebook. Retrieved from https://akss.dau.mil/dag/welcome.asp.

Department of Defense (2003), DoD supply chain materiel management regulation, DoD Regulation 4140.1. Washington: Government Printing Office.

Department of Defense (2014). DoD supply chain materiel management procedures: operational requirements, DoD Manual 4140.01, Volume 1. Washington: Government Printing Office.

deWinter, J. C. F. (2013). Using the Student's t-test with extremely small sample sizes. *Practical Assessment, Research & Evaluation, 18*(10), 1-12.

Dillman, D. A. (2000). Mail and internet surveys: the tailored design method. New York: Wiley.

Fiksel, J. (2006). Sustainability and resilience: toward a systems approach. *Sustainability: Science, Practice & Policy, 2*(2), 1-8.

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T. & Gunderson, L. (2004). Regime shifts, resilience and biodiversity in ecosystem management. *Annual Review of Ecology, Evolution, & Systematics, 35*(1), 557-581.

Gorman, C., Dale, S. S., Grossman, W., Klarreich, K., McDowell, J. & Whitaker, L. (2005). The importance of resilience. *Time Canada, 165*(3), 76-79.

Griffis, S. E., Goldsby, T. J. & Cooper, M. (2003). Web based and mail surveys: a comparison of response, data and cost. *Journal of Business Logistics, 24*(2), 237-258.

Kunreuther, H. (2006). Risk and reaction. *Harvard International Review, 28*(3), 37-42.

Jüttner, U. & Maklan, S. (2011). Supply chain resilience in the global financial crisis: an empirical study. *Supply Chain Management: an International Journal, 16*(4), 246-259.

Lambert, D. M., García-Dastugue, S. J., & Croxton, K. L. (2005). An evaluation of process-oriented supply chain management frameworks. *Journal of Business Logistics, 26*(1), 25-51.

Manuele, F. A. (2005). Risk assessment and hierarchies of control. *Professional Safety, 50*(5), 33-39.

Manuj, I, & Mentzer, J. T. (2008). Global supply chain risk management strategies. *International Journal of Physical Distribution & Logistics Management, 38*(3), 192-223.

Maronick, T. (2009). The role of the internet in survey research: guidelines for researchers and experts. *Journal of Global Business and Technology, 5*(1), 18-15.

McClave, J. T., Benson, P. G., & Sincich, T. (2008). Statistics for business and economics. Pearson Education.

Mentzer, J. T., DeWitt, W., Keebler, J., Soonhoong, M., Nix, N., Smith, C. & Zacharia, Z. (2001). Defining supply chain management. *Journal of Business Logistics, 22*(2), 1-25.

Merriam-Webster. (2007). Merriam-Webster dictionary, Springfield, MA: Merriam-Webster, Inc.

Peck, H. (2005). Drivers of supply chain vulnerability: an integrated framework. *International Journal of Physical Distribution & Logistics Management, 35*(4), 210-232.

Pettit, T. J., Croxton, K. L. & Fiksel, J. (2013). Ensuring supply chain resilience: development and implementation of an assessment tool. *Journal of Business Logistics, 34*(1), 46-76.

Pettit, T. J., Fiksel, J. & Croxton, K. L. (2010). Ensuring supply chain resilience: development of a conceptual framework. *Journal of Business Logistics, 31*(1), 1-21.

Ponomarov, S. Y., & Holcomb, M. C. (2009). Understanding the concept of supply chain resilience. *International Journal of Logistics Management, 20*(1), 124-143.

Ponis, S. T., & Koronis, E. (2012). Supply chain resilience: definition of concept and its formative elements. *Journal of Applied Business Research, 28*(5), 921-930.

Rice, J. A. (1995). Mathematical statistics and data analysis, 2nd Ed., Belmont: Duxbury Press.

Rice Jr., J. B. & Caniato, F. (2003). Building a secure and resilient supply network. *Supply Chain Management Review, 7*(5), 22-30.

Russell, S. H. (2007). Supply chain management: more than integrated logistics. *Air Force Journal of Logistics, 31*(2), 56-63.

Sheffi, Y. (2005a). Building a resilient supply chain. *Harvard Business Review,* 1(8), 1-4.

Sheffi, Y. (2005b). The resilient enterprise: overcoming vulnerability for competitive advantage. Cambridge, MA: MIT Press.

Stock, J. R., & Boyer, S. L. (2009). Developing a consensus definition of supply chain management: A qualitative study. *International Journal of Physical Distribution & Logistics Management, 39*(8), 690-711.

Stoltz, P. G. (2004). Building resilience for uncertain times. *Leader to Leader, Winter 2004*(31), 16-20.

The Ohio State University (2009). Ohio State secures Dow Chemical to sponsor global supply chain resilience research program. News Advisory. Retrieved from http://www.resilience.osu.edu/CFR-site/pdf/Dow_Resilience.pdf.

VanderBok, R., Sauter J. A., Bryan, C. & Horan, J. (2007). Manage your supply chain risk. *Manufacturing Engineering, 138*(3), 153-161.